Effect of initial water content and pore water chemistry on intrinsic compression behavior

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Abstract: Effect of initial water content (w_0) and pore water chemistry on the intrinsic compression curve of clays was investigated experimentally. The test results indicate that w_0 had a considerable effect on the intrinsic compression curve of a clay, and the degree of the effect is a function of pore water chemistry. The fundamental mechanism of the effect of w_0 and pore water chemistry on the intrinsic compression curve is through its influence on the microstructure of clays. For relatively stable flocculated microstructures, the effect of w_0 will disappear under a small value of effective vertical consolidation stress, σ'_v, for example $\sigma'_v <$ 20 kPa; under one-dimensional deformation condition, but for a dispersive microstructure, the effect of w_0 can remain up to $\sigma'_v >$ 1,000 kPa. Furthermore, it has been shown that when σ'_v is larger than the remolded yield stress, almost all the test data follow the intrinsic compression line (ICL) proposed by Burland. Finally, based on the test data, a new equation for estimating void ratio (e^*_{100}) under σ'_v = 100 kPa on ICL from the void ratio (e_l) corresponding to the liquid limit water content has been proposed.

Keywords: clay, clay, compression, initial water content, cation concentration

NOTATION

C^*_c = the intrinsic compression index calculated for vertical compression stress σ'_v from 100 kPa to 1,000 kPa (-)

e = void ratio (-)

e_l = void ratio corresponding to liquid limit water content (-)

e^*_{100} = void ratio on intrinsic compression line (ICL) under vertical consolidation stress, σ'_v = 100 kPa (-)

e' = elementary electric charge (= 1.602×10^{-19} C)

I_v = void index (-)

k = Boltzmann's constant (= 1.38×10^{-23} J/K)

n = molar concentration of cations in pore fluid (mole/m^3 multiplied by Avogadro's number $N_A = 6.023\times10^{23}$)

T = absolute temperature in Kelvins (K)

w_0 = initial water content (-)

w_l = liquid limit (-)

w_p = plastic limit (-)

ν = valence of cation (-)

ε = dielectric constant of pore fluid (C^{2}J^{-1}M^{-1})

κ = diffusive double layer (DDL) parameter ($1/\kappa$ = thickness of the DDL) (L^{-1})

σ'_v = vertical consolidation stress (ML^{-1} T^{-2})

σ'_{yr} = remolded yield stress (ML^{-1} T^{-2})

σ'_{yr1} = first "apparent" remolded yield stress (ML^{-1} T^{-2})

σ'_{yr2} = second "apparent" remolded yield stress (ML^{-1} T^{-2})

INTRODUCTION

Olson and Mesri (1970) reported that the compressive behavior of remolded clays is influenced and controlled by both the mechanical interaction (internal friction and deformation of the particles) and the physico-chemical forces (long range repulsive and attractive forces) between clay particles. It was suggested that for clays formed by more active clay minerals, such as smectite, at lower compression pressure, the effect of physico-chemical forces between clay particles will be more significant. It is well known that in a solution, clay particles will absorb cations to their surfaces to balance the negative charges they are carrying on the surfaces and the system is called diffusive double layer (DDL) (Gouy 1910; Chapman 1913). The repulsive force between clay particles is directly related to the thickness of DDL.

Hong et al. (2010) reported that initial water content (w_0) influenced compression curves of clays. The value of w_0 will influence the initial microstructure of clays, i.e. the arrangement of clay particles, and then the compression behavior of the clays. The value of w_0 not only influences the mechanical interaction between clay particles, but also the physico-chemical behavior of a clay. Normally under a given consolidation stress, the higher the value of w_0, the higher the resulting void ratio (e). There are reports in the literature that even under a vertical consolidation stress of more than 1,000 kPa, the effect of w_0 still remained (e.g. Hong et al. 2013; Zeng, et al. 2015). For the clays tested by Hong et al. (2013) and Zeng et al. (2015), the main clay mineral is illite.

Conceptually, the degree of the effect of w_0 on the intrinsic compression behavior of clay is influenced by the pore water chemistry of the clay also. While there is no detailed investigation about the interaction of w_0 and pore chemistry on the intrinsic compression behavior of clays. Furthermore, for clays, Burland (1990) proposed a unique relationship for intrinsic compression line (ICL) in void index (I_v) versus effective vertical consolidation stress (σ'_v) curve for w_0 between liquid limit (w_L) and 1.5w_L (mostly for 1.25w_L) and σ'_v from 10 kPa to 4000 kPa. Hong et al. (2010) refined the ICL to be applicable for w_0 = (0.7 - 2.0)w_L and σ'_v = 1.5 - 1600 kPa, and named it as extended intrinsic compression line (EICL). In EICL, w_0 has been included in the equation used for calculating I_v. Hong et al. showed that the EICL is almost identical with ICL for σ'_v > 25 kPa. Here, there is a question, that, are the equations for ICL and EICL applicable for clays with different pore chemistry?

In many Asian countries, such as China, recent years' of economic development demand more land in coastal areas and many land reclamation projects have been carried out. Since the shortage of sandy fill materials, dredged clayey soils from the sea beds or river beds have been used as filler materials (e.g. Tang et al. 2013). Additionally, every year the maintenance of ports has generated a large amount of clayey soils with high water content and different pore chemistry, and their treatment is a geoenvironmental problem. Furthermore, there are a lot of offshore geotechnical projects encountered with marine clays (Chu et al. 2009; Zhao et al. 2017). Due to different source minerals and depositional environment, generally pore water of marine clay at different place contains different chemical substances. Therefore, understanding the consolidation-compression behavior of clayey soils with high values of w_0 and different pore water chemistry has an important engineering implication.

In this study, both the effects of w_0 and pore water chemistry on intrinsic compression behavior of clays have been investigated experimentally by three (3) series of consolidation tests. One series used remolded natural clay with the dominant clay mineral consisting of smectite. One series used dredged clay from a river mouth (where the river water meets the sea water), and one series used the same natural Ariake clay as the series specimen, but with the addition of artificially derived $CaCl_2$ (a flocculation agent) into the pore water. The test results are compared quantitatively and possible interaction mechanisms of w_0 and pore water chemistry on the intrinsic compression behavior of the clays, and the applicability of the equations for ICL and/or EICL to the soils tested are discussed.

LABORATORY CONSOLIDATION TESTS

Test devices

For a standard multi-stage-loading (MSL) consolidation test, the first stage load is normally 5 to 10 kPa. While for clays with a high value of w_0 (more than $1.5w_L$), its consolidation process may start from a pressure less than 1.0 kPa. In this study, a consolidation device which can be used to conduct the consolidation test with the first load of 0.5 kPa was developed. The picture and the sketch of the device are shown in Figs 1(a) and (b) respectively.

The consolidation device mainly consists of a consolidation chamber, a consolidation ring, a dead load loading system and a laser displacement measurement gauge. The consolidation ring has a diameter of 60 mm, and height of 30 mm. The standard MSL consolidation ring has a height of 20 mm, but considering the large compression deformation of a clay specimen with a high value of w_0, a height of 30 mm was adopted. Under a lower consolidation stress, if using a spring type Linear Variable Differential Transformer (LVDT) to measure the displacement, the spring force from the LVDT may have an influence on the load balance on the specimen. A laser displacement gauge was used to measure the vertical displacement. The vertical consolidation stress was applied using dead loads (aluminum discs) up to 128 kPa, and to ensure centric load application, three guide rods were used to fix the position of the discs. The duration of each load increment was 1 day. Upon conclusion of the consolidation test under 128 kPa, the consolidation ring with the soil specimen inside was moved to a standard MSL consolidation device, and vertical consolidation stresses of 256, 512 and 1024 kPa (for part of the tests) were applied step by step. For each load increment, the settlement-time curve was recorded by a computer through a data-log.

Materials and cases tested

Two types of clay were tested. One was remolded Ariake clay (Chai et al. 2017) and another was dredged clay. The remolded Ariake clay was sampled from Ashikari-Tyo, Saga Prefecture, Japan, at about 2.0 m depth from the ground surface. The dredged clay was obtained from the mouth of Kasegawa River where at high tide, the sea water from Ariake Sea can enter the river. The grain size distributions of the clays are shown in Fig. 2. To investigate the effect of pore water chemistry on the compression behavior of clays, one series tests were conducted using the Ariake clay but adding 3% $CaCl_2$ into the pore water. The liquid limits and plastic limits (w_p) of the soils are listed in Table 1. In the literature there are reports indicating that pore fluid chemistry has a considerable influence on w_L of clays (e.g., Bjerrum, 1967). There are two possible mechanisms explaining the effect of pore chemistry on w_L. One is influences the thickness of the diffusive double layer (DDL) ($1/\kappa$) around clay particles and another influences the microstructure of a clay (Sridharan and Prekash 1999). For example, increasing cation concentration in the pore water can reduce $1/\kappa$, which intends to reduce w_L. While reducing $1/\kappa$ can promote face-edge contacts between clay particles, which has a tendency to form flocculated microstructure and hold more water in the micro-pores and then increase w_L. It is possible that the clay that tested these two effects somehow cancelled each other; adding 3% $CaCl_2$ did not have a considerable effect on w_L.

For each soil, the value of w_0 were varied in a range of about 1.1 to 1.7 times the corresponding liquid limits. The cases tested are listed in Table 2.

Test results

The results of void ratio, e, versus $\log(\sigma'_v)$ curves of using the Ariake clay samples with different value of w_0 are shown in Fig. 3. It is clearly shown that the value of w_0 had an obvious effect on the compression behavior of the specimen. The higher the value of w_0, the higher the resulting value of e under a given σ'_v. The results are similar to that reported by

Hong et al. (2010).

Since most soils with a high value of w_0 are dredged clays from ports and sea beds, consolidation tests using the dredged clay with different value of w_0 were carried out and the results are shown in Fig. 4. It can be seen that the degrees of influence of w_0 on the compression behavior of the dredged clay are quite different from that of the Ariake clay. For the Ariake clay, the effect of w_0 remained for the whole stress range tested (0.5 – 512 kPa). While for the dredged clay, when the vertical consolidation stress was larger than about 20 kPa, there was almost no difference on e – log(σ'_v) plots with different value of w_0.

The results in Figs 3 and 4 indicate that the degree of the effect of w_0 on the compression behavior of clays also depends on soil types. As indicated in Table 1 and Fig. 2, in terms of w_l, w_p and grain size distribution, the difference between the Ariake clay and the dredged clay is not very significant. Then it was thought that there might be some difference on pore water chemistry for the two types of clay. The concentrations of four cations (Ca^{++}, Mg^{++}, Na^{+} and K^{+}) in the pore water were measured and the results are listed in Table 1 also. The pore waters were obtained from soil samples with an initial water content of about 180% by a centrifuge. It can be seen that there is an obvious difference for the two clays. The concentration of Na^{+} in the pore water of the dredged clay is much higher than that of the Ariake clay. The cation concentration might have an effect on the compression behavior of the clays. To confirm this point a series of consolidation tests using Ariake clay but with the addition of 3% of $CaCl_2$ as a flocculation agent into the pore water. The test results are shown in Fig. 5. Similar to the dredged clay, when adding 3% $CaCl_2$ into the pore water of the Ariake clay, w_0 only had an influence on compression behavior for consolidation pressure less than about 20 kPa.

Based on the test results presented above, it is suggested that the effect of w_0 on intrinsic compression curves of clay can be divided into two types for ease of later discussion. Type-I, the effect exists in the whole range of the compression pressure (up to 1,000 kPa); and Type –

II, the effect only exists for σ'_v < 100 kPa. The results of the Ariake clay belongs to Type-I and the results of the dredged clay and the Ariake clay + 3% $CaCl_2$ belong to Type-II.

ANALYSES AND DISCUSSIONS

Mechanism and Remolded Yield Stress

The fundamental mechanism of the effect of w_0 on the intrinsic compression behavior of a clay is through the effect of the microstructure of the clay. Although the microstructure of clays is complicated, ideally they can be classified into two groups: flocculated and dispersed microstructures. When DDL around clay particles is thin, the face-edge contacts (negative charges on the face and positive charges on the edge) can be formed and several clay particles may form a "stable" aggregate (Fig. 6(a)). The value of w_0 will influence the initial spacing between aggregates, but since the DDL around the clay particles is thin, under a relative lower consolidation pressure, the effect of w_0 on the spacing between aggregates will be eliminated. While if the DDL is thick, the repulsive force between clay particles will be high and face-edge contacts cannot be formed and the clay particles will be separated from each other in the pore water. The higher the value of w_0, the more freedom for clay particles to align randomly (Fig. 6(b) (i)). And if the value of w_0 is lower, the platelet clay particles may be aligned in certain dominated direction (Fig. 6(b) (ii)). This kind of initial difference of microstructure of clay particles may be remained even with a consolidation pressure of more than 1,000 kPa.

For a solution with single cation, the DDL parameter, κ, can be calculated by the following equation (Gouy 1910; Chapman 1913):

$$\kappa = \sqrt{\frac{2(e')^2 v^2 n}{\varepsilon k T}} \tag{1}$$

where v = valence of cation, e' = elementary electric charge (= 1.602×10^{-19} C), ε = dielectric constant of pore fluid (for water, ε = 7.083×10^{-10} $C^2J^{-1}M^{-1}$), n = molar concentration of cations in pore fluid (mole/m^3 multiplied by Avogadro's number N_A = 6.023×10^{23}), k = Boltzmann's constant (= 1.38×10^{-23} J/K), T = absolute temperature in Kelvins. As listed in Table 1, the solutions had multi-cations. Sridharan and Jayadeva (1982) proposed an approximate pragmatic method for multi-cations case, in which the value of n in the solution can be summed up for cations existed in the solution; and the value of ν can be calculated as the weighted average value by the values of molar concentration. With the cation concentrations in Table 1 and adopting Sridharan and Javadeva's approach, the total values of n and the equivalent values of ν for the pore water in the soil specimens are summarized in Table 3. Then using Eq. (1), the calculated thicknesses ($1/\kappa$) of DDL are also listed in Table 3. It can be seen at least qualitatively that the Ariake clay has a larger value of $1/\kappa$ than that the dredged clay and the Ariake clay adding 3% $CaCl_2$ into the pore water. As a tendency, the values in Table 3 support the argument made above.

Hong et al. (2010) reported some results of consolidation test of remolded clays with high value of w_0. The results show that in a ln(1+e) – ln(σ'_v) plot, the compression curves are bi-linear, and the pressure at the intersect of the two lines is defined as "remolded yield stress" (σ'_{yr}) (Hong et al. 2012). And σ'_{yr} is analogue to pre-consolidation stress for natural undisturbed soil. For the Ariake clay tested in this study, ln(1+e) – ln(σ'_v) plots are close to bi-linear, but for the dredged clay and the Ariake clay adding 3% $CaCl_2$ into the pore water cases, the initial parts of the most curves are not in bi-linear form. Figure 7 shows the ln(1+e) – ln(σ'_v) plots of the dredged clay. It can be seen that the initial parts are curved and may be approximated as a tri-linear form. If define the pressures at the intersect of the first (beginning part) and the middle parts of the tri-linear as remolded yield stress-1 (σ'_{yr1}) and the middle and the last parts of the tri-linear as remolded yield stress-2 (σ'_{yr2}), e_0/e_l versus σ'_{yr} (including σ'_{yr1} and σ'_{yr2}) relationships together with the relationship ($\sigma'_{yr} = 5.66(e_0/e_l)^2$) proposed by Hong et al. (2010) are shown in Fig. 8. Where e_0 is initial void ratio and e_l is the void ratio corresponding to liquid limit water content. It can be seen that for the Ariake clay, the data points are close to the relationship proposed by Hong et al. (2010), but for the dredged clay and the Ariake clay adding 3% $CaCl_2$ into the pore water cases, the most data points of σ'_{yr2} are above and the most data points of σ'_{yr1} are below the proposed curve. For the cases tested, the value of σ'_{yr1} is about 2.0 kPa. It can be postulated that for clays with a flocculated microstructure, σ'_{yr1} may be the pressure from which the inter-aggregate spacing starts to reduce, and σ'_{yr2} may be the pressure from which the intra-aggregate spacing starts to reduce.

Intrinsic compression line (ICL) and extended ICL

Intrinsic compression line (ICL) is defined as the one-dimensional consolidation line using reconstituted soil with an initial water content between the liquid limit (w_L) and 1.5w_L. Instead of using void ratio, Burland (1990) defined I_v as follow:

$$I_v = \frac{e - e^*_{100}}{C^*_c} \tag{2}$$

where e is void ratio, e^*_{100} is the void ratio on ICL under σ'_v = 100 kPa, and C^*_c is the intrinsic compression index calculated for σ'_v from 100 kPa to 1,000 kPa.

Then ICL in log(σ'_v) versus I_v plot is expressed as (Burland 1990):

$$I_v = 2.45 - 1.285 \cdot \log\sigma'_v + 0.015 \cdot (\log\sigma'_v)^3 \tag{3}$$

Hong et al. (2010) extended ICL to EICL with w_0 = (0.7 - 2.0)w_L and σ'_v = 1.5 - 1600 kPa and the expression is as follows:

$$I_v = 3.0 - 1.87 \cdot \log \sigma'_v + 0.179 \cdot (\log \sigma'_v)^2 \tag{4}$$

The test results from this study are plotted in Figs 9 to 11 and compared with Eqs (3) and (4) (σ'_v >= 1 kPa) for the Ariake clay, the dredged clay and the Ariake clay + 3% $CaCl_2$. When σ'_v is larger than the remolded yield stress (σ'_{yr} or σ'_{yr2}), all lines follow the ICL (Eq. (3)).

Estimating e^*_{100} and C^*_c

Burland (1990) suggested that e^*_{100} and C^*_c can be estimated from e_l as:

$$e^*_{100} = 0.109 + 0.679 \cdot e_l - 0.089 \cdot e_l^2 + 0.016 \cdot e_l^3 \tag{5}$$

$$C^*_c = 0.256 \cdot e_l - 0.04 \tag{6}$$

Zeng et al. (2015) modified the equations for estimating e^*_{100} and C^*_c (Eqs (5) and (6)) for clays with $w_0 > 1.5w_L$ as follows:

$$e^*_{100} = 0.223 + 0.261 \cdot e_0 + 0.282 \cdot e_l - 0.018 \cdot e_0 - 0.05 \cdot e_l^2 + 0.015 \cdot e_l^3 \tag{7}$$

$$C^*_c = -0.064 + 0.153 \cdot e_0 + 0.11 \cdot e_l - 0.006 \cdot e_0^2 \tag{8}$$

The measured and estimated (Eqs (5) and (7)) values of e^*_{100} are compared in Fig. 12. It clearly shows that the estimated values by both Eqs. (5) and (7) are much lower than the measured ones. It was reported by Chai et al. (2017) that for both Holocene and Pleistocene clays in Saga Plain, Japan, if using e^*_{100} from Eq. (5), the one-dimensional compression curves of the undisturbed clay samples were all above the sedimentation compression line (SCL) proposed by Burland (1990), which is abnormal when compared with the test data reported by Burland (1990). The reason has been identified that Eq. (5) underestimated the value of e^*_{100} of clays in Saga Plain. The measured values of e_l and e^*_{100} from this study, and the data reported by Chai et al. (2017) and Nakase et al. (1988) for some clays (including some clay and sand mixtures) in Japan are plotted in Fig. 13. Then a new equation for estimating e^*_{100} from e_l has been proposed as:

$$e^*_{100} = 0.3 + 0.35e_l + 0.09 \cdot e_l^2 \tag{9}$$

Eq. (9) does not consider the effect of w_0. It is suggested that Eq. (9) can be applied to Type-II clays, and for Type-I clays, the equation can only be applied for w_0 in a range of w_l to $1.5w_l$. The predicted values of e^*_{100} for the tested cases reported in this study are included into Fig. 12 also.

The measured and the estimated (Eqs (6) and (8)) values of C^*_c are compared in Fig. 14. For the Ariake clay and the Ariake clay + 3% CaCl2, the measured values of C^*_c are for vertical compression stress from 100 kPa to 512 kPa. It can be seen that for the dredged clay and the Ariake clay + 3% $CaCl_2$ (Type-II), Eq. (6) resulted a quite good prediction. While for the Ariake clay (Type-I), Eq. (8) which considering the effect of w_0 yielded better estimations. Therefore, it is suggested that for Type-I using Eq. (8) and for Type-II using Eq. (6).

CONCLUSIONS

Effect of initial water content (w_0) and pore water chemistry on intrinsic compression behavior of clays was investigated experimentally. Based on the test results, the following conclusions can be drawn.

(1) The value of w_0 had a considerable effect on void ratio (e) versus effective vertical consolidation stress (σ'_v) relationships of clay. Within the stress range the effect of w_0 exists, under a given σ'_v, the higher the w_0, the larger the value of e. The degree of the effect of w_0 is a function of pore water chemistry. Increasing cation concentration in the pore water of a clay, reducing the degree of the effect of w_0 on its compression curve.

(2) It is interpreted that the fundamental mechanism of the effect of w_0 and pore water chemistry is through influencing the microstructures of clay. With a relative high cation concentration in the pore water, the diffusive double layer (DDL) around clay particles will be thin and the clay particles can form a relative stable flocculated microstructure, the effect of w_0 will disappear under a small σ'_v, for example, σ'_v < 20 kPa. In case the

dispersive inter-particle connections dominated in the system, the effect of w_0 can remain up to σ'_v > 1,000 kPa.

(3) The test results were analyzed using intrinsic compression line (ICL) proposed by Burland and the extended ICL (EICL) by Hong et al. It has been shown that when σ'_v is larger than remolded yield stress, almost all the test data follow Burland's ICL. Void ratio (e^*_{100}) under σ'_v = 100 kPa on ICL is one of the key parameters needed for calculating void index. It has been found that all existing methods for estimating e^*_{100} from the void ratio (e_l) corresponding to the liquid limit water content under evaluated the values of e^*_{100} of the clays tested and a new equation (Eq. (9)) has been proposed.

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Table 1 Liquid and plastic limits and cation concentrations in the pore waters

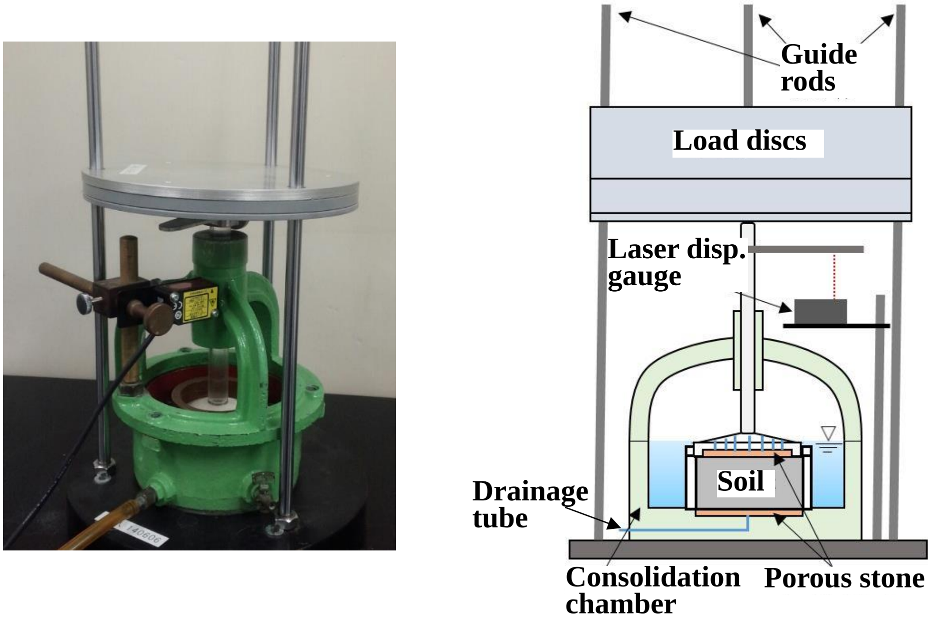
Soil	Specific gravity	w_l (%)	w_p (%)	Cation concentration (ppm)			
				Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
Ariake clay	2.568	107.0	40.7	53	89	233	51
Dredged clay	2.572	105.6	50.7	88	159	1,112	100
Ariake clay + 3%$CaCl_2$	-	104.0	42.7	9,821	958	413	198

Table 2 Cases tested

Soil	Case	w_0 (%)	Consolidation stress range (kPa)
Ariake clay	AC-1	118	0.5 – 512.0
	AC-2	136	
	AC-3	158	
	AC-4	178	
Dredged clay	DC-1	113	0.5 – 1024.0
	DC-2	119	
	DC-3	136	
	DC-4	156	
	DC-5	167	
Ariake clay + 3%$CaCl_2$	AC-a	114	0.5 – 512.0
	AC-b	139	
	AC-c	157	

Table 3 Calculated thickness of DDL

Soil	n (mole)	Equivalent value of ν	$1/\kappa$ (Å)
Ariake clay	0.016	1.304	18.24
Dredged clay	0.060	1.146	10.87
Ariake clay + 3%$CaCl_2$	0.307	1.925	2.85



(a) Picture (b) Sketch

Fig. 1 One-dimensional consolidation device

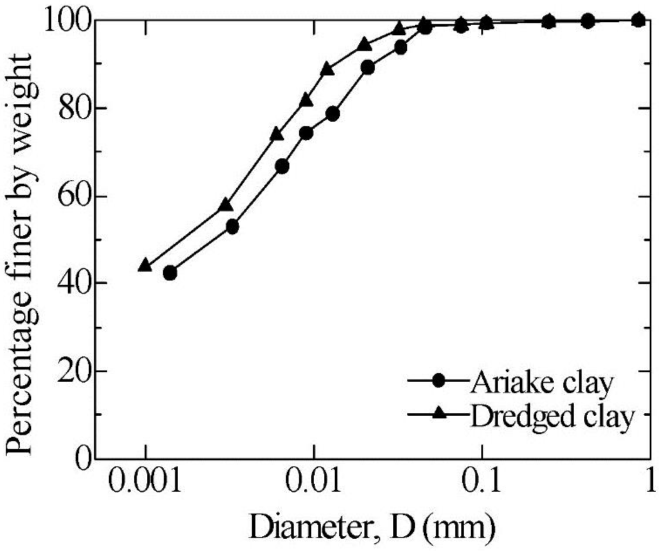


Fig. 2 Grain size distributions

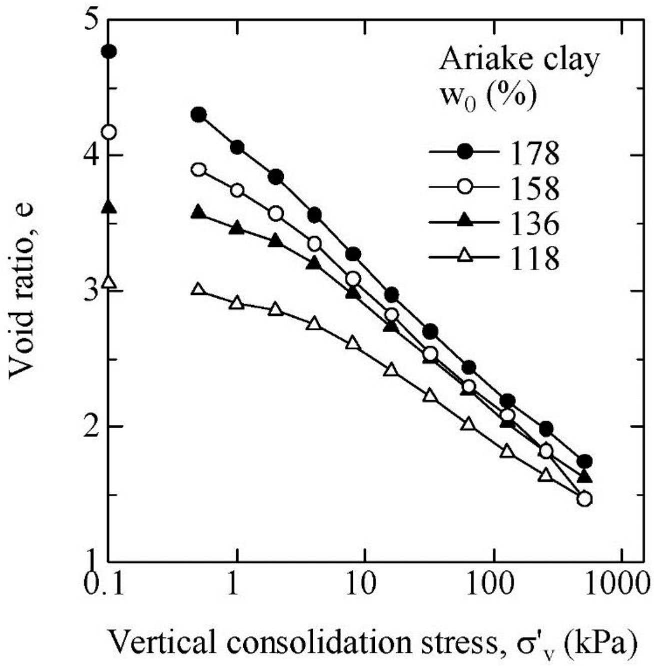


Fig. 3 $e - \log(\sigma'_v)$ curves of the Ariake clay

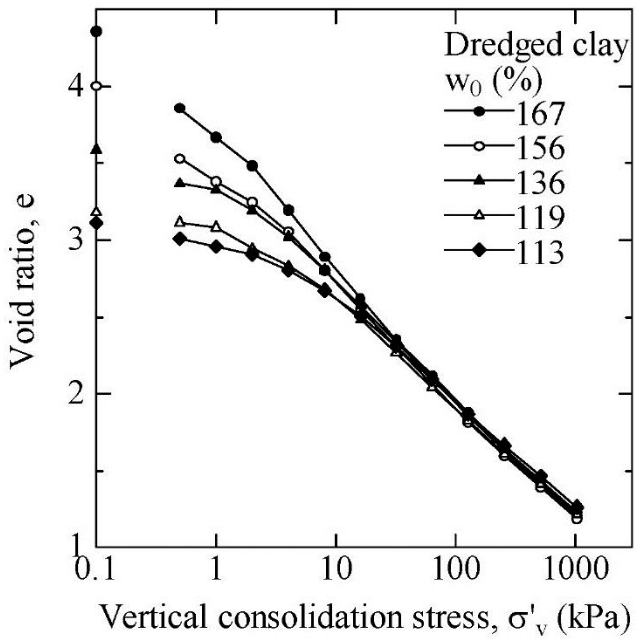


Fig. 4 $e - \log(\sigma'_v)$ curves of the dredged clay

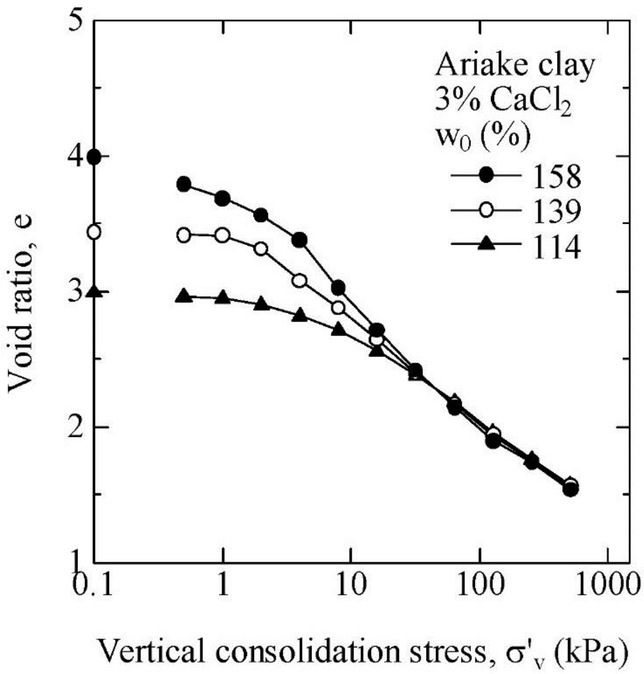


Fig. 5 $e - \log(\sigma'_v)$ curves of the Ariake clay with $CaCl_2$ additive

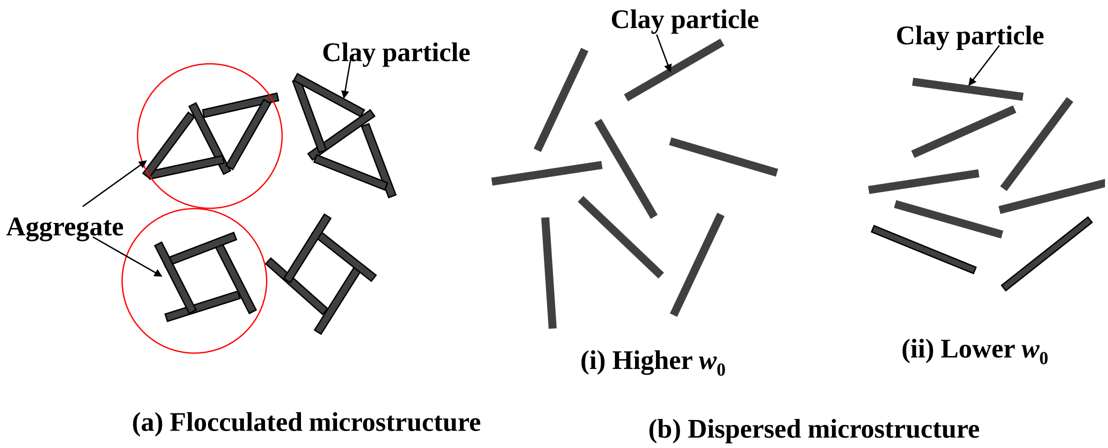


Fig. 6 Illustration of flocculate and dispersive microstructures of clay

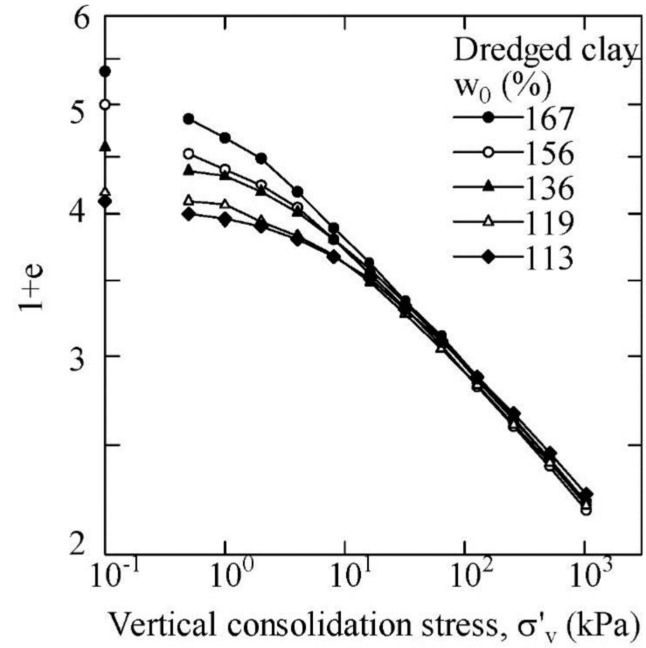


Fig. 7 ln(1+e) – log(σ'_v) curves of the dredged clay

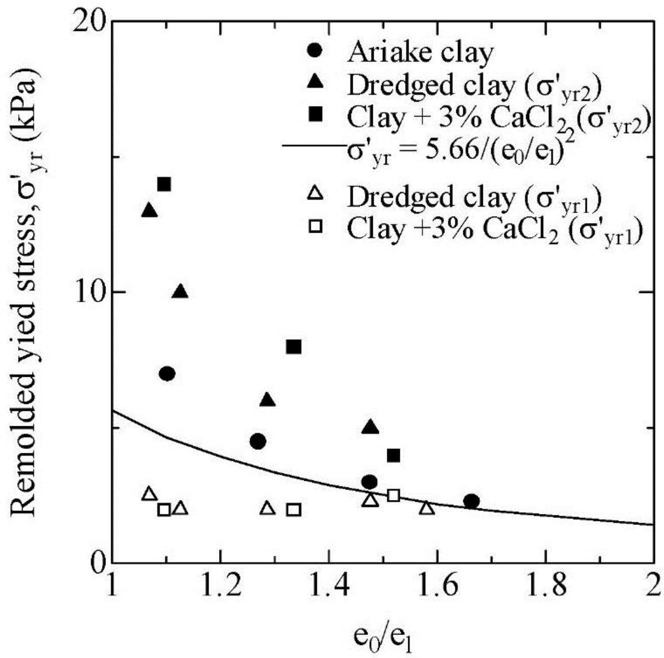


Fig. 8 e_0/e_l versus σ'_{yr} relationships

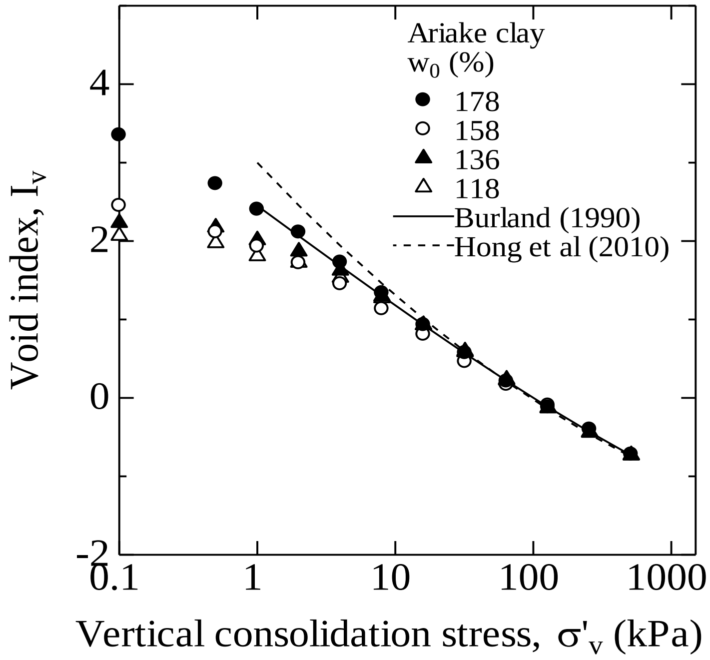


Fig. 9 Intrinsic compresion curves of the Ariake clay

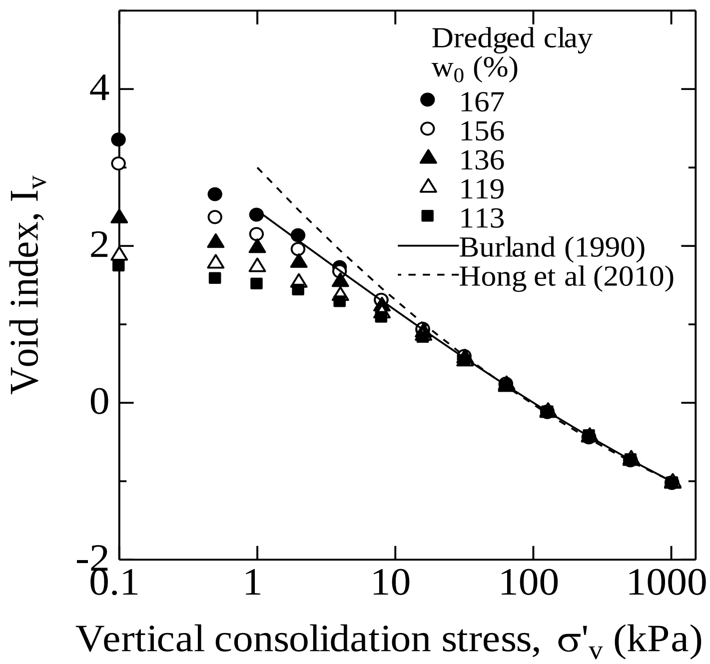


Fig. 10 Intrinsic compresion curves of the dredged clay

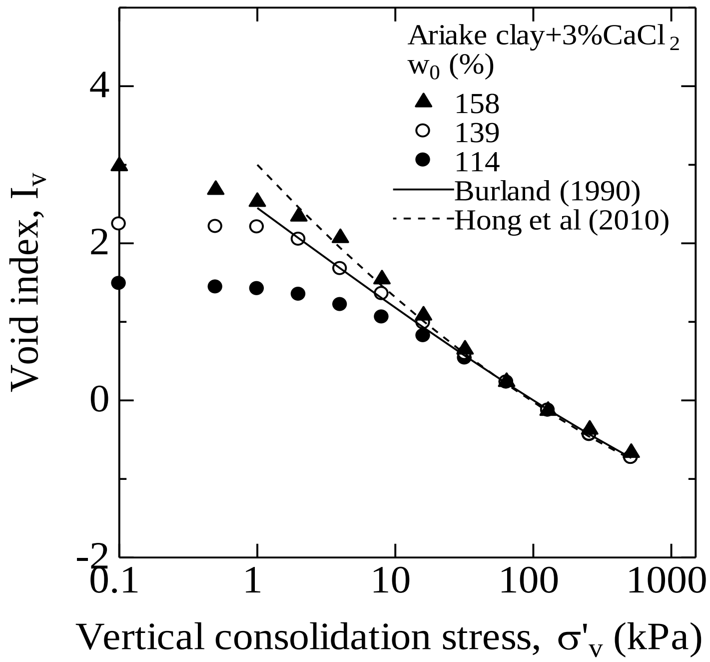


Fig. 11 Intrinsic compresion curves of the Ariake clay + 3% $CaCl_2$

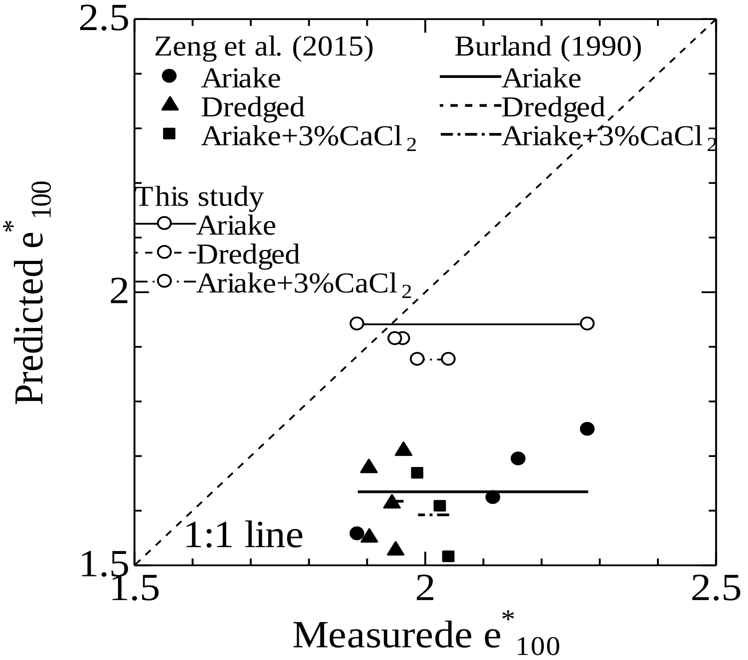


Fig. 12 Comparison of measured and estimated values of e^*_{100}

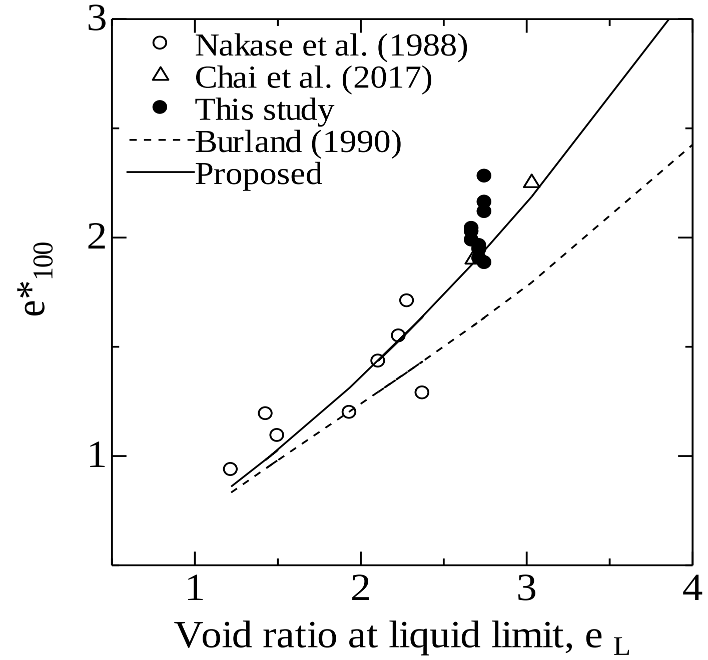


Fig. 13 Relationships between e^*_{100} and e_l

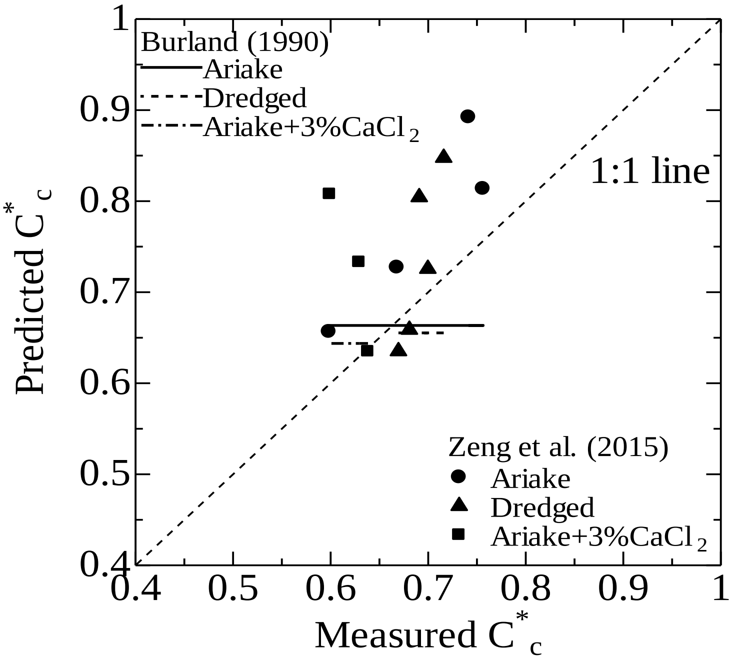


Fig. 14 Comparison of measured and estimated values of C^*_c